

WHERE TO FIND HABITABLE "EARTHS" IN CIRCUMBINARY SYSTEMS

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ABSTRACT

Hitherto, six P-type planets are found around five binary systems, i.e. Kepler-16 b, 34 b, 35 b, 38 b, 47 b, c, which are all Neptune or Jupiter-like planets. The stability of planets and the habitable zones are influenced by the gravitational and radiative perturbations of binary companions. In this Letter, we check the stability of an additional habitable Earth-mass planet in each system. Based on our simulations in 10 Myr, a habitable "Earth" is hardly stable in Kepler-16 while a stable "Earth" in Kepler-47 close to the boundaries of the habitable zone is possible. In contrast, Kepler-34, 35 and 38 seem to have high probabilities of being able to tolerate a stable "Earth" in their habitable zones. The affects of transit time variations are quite small due to the small mass of an undetected "Earth", except that of Kepler-16 b. With a time precision of 10^{-3} day (~ 88 s), an "Earth" in the corotational resonance with Kepler-16 b can be detected in 3 years, while habitable "Earths" in Kepler-34 and 38 systems can be detected in 10 years. Habitable "Earths" in Kepler-35 and 47 are not likely to be detected in 10 years under this precision.

Subject headings: stars: individual: (Kepler-16, 34, 35, 38, 47)

1. INTRODUCTION

Searches for Earth-like exoplanets, especially the Kepler mission, make great contributions to our knowledge about terrestrial planets. To date, about 66 Earth-like ($< 10M_{\oplus}$) planets are confirmed¹ and more than 1100 candidates with radii $R_p < 2R_{\oplus}$ are detected.² Considering these Earth-like planets with minimum masses $< 10M_{\oplus}$, only few of them have a moderate equilibrium temperature and are considered as habitable planets (Kopparapu et al., 2013), e.g., HD40307 g (Tuomi et al., 2012) and GJ667C c (Delfosse et al., 2012). Meanwhile, 11 candidates with radii $< 2R_{\oplus}$ are in the habitable zone (Gaidos, 2013). Habitable Earth-like planets are likely to stay in more compacted multi-planet systems. For example, HD40307 contains six planets and GJ667C has at least two planets.

Planets in habitable zone (hereafter HZ) must have a moderate temperature to maintain liquid water on the surface and have a possibility of sustaining life (Kasting et al., 1993; Jones et al., 2001). The temperature of a planet is usually considered via several conditions (Gaidos, 2013), e.g., planetary albedo, orbital eccentricity and obliquity (Williams & Pollard, 2003), components of the planetary atmosphere (Pierrehumbert et al., 2011), etc. In single star systems, the HZ is fixed due to the stable flux of the host star in main sequences. However, the HZ in binary systems is different due to the radiative perturbation of the binary companion. Eggl et al., (2012) provided an analytic method to estimate the HZs for S-type planetary orbits, and pointed out that HZs are strongly affected by the eccentricity of the binary. Kane & Hinkel (2013) studied HZs for P-type planetary orbits, which would oscillate with time due to the different orbital phases of the

binary stars. The stabilities of planets in binary systems are also different from those in single star systems (Holman & Wiegert 1999). Considering a multi-planet system, planets with equal masses are stable in single star systems if their separations exceed a critical value $\sim 7 - 10$ Hill radii (Chambers et al., 1996; Zhou et al., 2007). Adding the perturbation of a binary companion, the stabilities of planets around the binary are queried.

In this Letter, we focus on the five circumbinary systems: Kepler-16 (Doyle et al., 2011), 34, 35 (Welsh et al., 2012), 38 (Oroze et al., 2012b) and 47 (Oroze et al., 2012a). All six planets detected are Jupiter-like or Neptune-like planets (see Table 1), which probably have a thick atmosphere and may not form a solid surface, thus they are not suitable for life. As noted by Gong et al., (2013), the formation of habitable Earth-like planets in circumbinary systems is possible. Here we assume that an additional "Earth" formed in these systems to obtain the tolerant regions of stable habitable "Earths". We also simulate the transit time variations (hereafter TTVs) of the existing planets with and without an additional "Earth". The differences between these two TTVs may help us to predict the existence of an undetected "Earth" through further observations (Agol et al., 2005; Lithwick et al., 2012).

2. ADDITION-"EARTH" MODEL

Researchers usually estimate the boundaries of HZ via the maximum greenhouse effects provided by a CO₂ atmosphere and via runaway greenhouse effect (i.e., loss of water, (Kasting et al., 1993; Underwood et al., 2003)). As Kopparapu et al., (2013) pointed out most recently, the stellar fluxes (with unit 1368 W m^{-2}) at the boundaries of HZ are

$$S_{\text{in}} = S_{\text{eff}\odot} + aT_* + bT_*^2 + cT_*^3 + dT_*^4, \quad (1)$$

$$S_{\text{out}} = S_{\text{eff}\odot} + aT_* + bT_*^2 + cT_*^3 + dT_*^4, \quad (2)$$

¹ Data from <http://exoplanets.org>

² Data from <http://www.nasa.gov>

where $T_* = T_{\text{eff}} - 5780\text{K}$ and the value of $S_{\text{eff}\odot}, a, b, c$ and d are listed in Kopparapu et al., (2013), see Tab.3 therein. In single star systems, T_{eff} is the effective temperature of the star. In binary systems, the equivalent T_{eff} of the binary are calculated by Wien's displacement law after combining the stellar spectral radiances of binary stars (see Section 3.2 in Kane & Hinkel (2013)).

The equilibrium temperature of a planet T_p is determined in two steps. (1) Estimate the combined flux on the planet S by $S = S_1 + S_2$, where $S_i = \sigma(1 - \alpha)(R_i/r_i)^2 T_{\text{eff},i}^4$, ($i=1,2$), where σ is the Boltzmann constant, α is the albedo of the planets, R_i is the radius of star i , r_i is the distance between the planet and star i and $T_{\text{eff},i}$ is the effective temperature of star i . (2) Estimate T_p of the planet by energy equilibrium: $\pi r_p^2 \times S = 4\pi\sigma r_p^2 T_p^4$, therefore we obtain

$$T_p = (S/4\sigma)^{1/4}. \quad (3)$$

Substituting Equations (1) and (2) into Equations (3), we get the temperatures at the HZ boundary, T_{in} and T_{out} . Note that T_{in} and T_{out} are independent of albedo α , but the location of the HZ depends on α in the expression of S_1 and S_2 .

The configurations of the five observed circumbinary systems are listed in Table 1 according to observations. We simulate 100 cases for each system. In each case, we put an additional "Earth" with a mass = $1M_{\oplus}$ and let the "Earth" evolve under the gravities of both binaries and the existing planets. All these "Earths" are put in circular orbits with an inclination = 1° initially; the phase angles of the "Earths" are chosen randomly. The initial locations of these "Earths" in each systems are interpreted in Section 3. Using the MERCURY package for N -body simulations (Chambers 1999), we estimate their stabilities and habitats based on our simulations. Due to the variation of T_p , only those "Earths" with $T_p(t) \in [T_{\text{out}}, T_{\text{in}}]$ are considered habitable in this work.

3. RESULTS IN FIVE SYSTEMS

3.1. Kepler-16

The equivalent temperature of binaries in the Kepler-16 system is $T_{\text{eff}} = 4307.8\text{K}$, and the HZ with temperatures $[200.2\text{K}, 271.6\text{K}]$ (Figure 1(a)) is located from 0.4 to 0.75 AU approximately. The locations of HZ boundaries change little with time because of the small contribution to the combined flux from the much cooler companion star. Note that the locations of HZ boundaries here are averaged by different azimuths. According to Quarles et al., (2012), "Earths" inside 0.66 AU ($\approx 222\text{K}$) are unstable in the system. The initial locations of our 100 "Earths" are chosen between $[173\text{K}, 222\text{K}]$ randomly.

The red/blue circles represent the initial locations of unstable/stable "Earths" during our simulations (the same notations are used in all figures hereafter). After 10 Myr evolution, more than 90% of "Earths" are ejected mainly due to the perturbations of Kepler-16 b, and only seven "Earths" survive outside the HZ. The orbits of other detected giant planets are also allowed to evolve under the gravities of planets and stars in our simulations. However, due to the large mass of Kepler-16 b, if the "Earth" is stable, the orbits of the presently observed planets are nearly unchanged. The same is true for other systems in Section 3. Finally, we obtain a null

"Earth" in the HZ of the Kepler-16 systems. As shown in Figure 1(b), we find two stable regions: $r \sim 0.72$ and 0.95AU . The inner two are in the corotational resonance with Kepler-16 b. Averaged by the time, their mean $T_p \approx 207.5$ and 207.4K , with variations about 19.7 and 16.2K . Therefore, these two "Earths" could be in the HZ only by considering some other different atmosphere models.

We set the albedo $\alpha = 0$ in Figure 1. If we change the albedo to $\alpha = 0.3$ comparable with the Earth and a higher value 0.5 to model metal-rich planets with a smooth surface, the equilibrium temperature of planets T_p becomes 0.915 and 0.841 times of that with $\alpha = 0$. The two planets in the same orbit with Kepler-16 b will obtain a lower $T_p \sim 189.8\text{K}$ for $\alpha = 0.3$ and $T_p \sim 174.5\text{K}$ for $\alpha = 0.5$, which no longer seems likely to be habitable.

3.2. Kepler-34

The T_{eff} of Kepler-34 binary is 5892K , and an "Earth" with T_p in $[214.2\text{K}, 282.9\text{K}]$ is habitable (Figure 2(a)). The HZ is about $1.6\text{--}2.8\text{AU}$ according to the fitting curve of T_p in Figure 2(b) (hereafter the same). The HZ boundaries vary with time more obviously than others because of the large eccentricity of binary stars and their similar T_{eff} . However, the variation of the inner HZ boundary is still very small ($< 0.02\text{AU}$) since the HZ is far away from the binary compared with the separation of binaries. The initial locations of our 100 "Earths" are chosen between $[173\text{K}, 570\text{K}]$ randomly.

The green filled circles represent the initial locations of stable habitable "Earths" (hereafter the same). Comparing with Kepler-16, the HZ in Kepler-34 is more stable for an additional "Earth". As shown in Figure 2(a), 74 "Earths" far away from Kepler-34 b easily survive after 10 Myr including 32 (75%) of the initial habitable "Earths" that remained in the HZ throughout that time. Figure 2(b) shows the locations of the 74 stable "Earths" and their T_p . The $T_p(r)$ is similar to that in single star systems as a power law: $T_p = 359.1\text{K}(r/1\text{AU})^{-1/2}$. We find a stable boundary of about 1.5AU , outside which "Earths" are stable. The mean distance of the outer HZ boundary is about 2.8AU . Thus, the Kepler-34 system is likely to tolerate a habitable "Earth" between 1.6 and 2.8AU when $\alpha = 0$. Due to the perturbation of Kepler-34 b, "Earths" close to it have a larger variations of T_p .

Changing the albedo α to 0.3 and 0.5 , the location of the HZ changed to an inner region, thus the outer boundary of HZ becomes 2.34AU for $\alpha = 0.3$ and 1.98AU for $\alpha = 0.5$. Overlapping with the stable boundary $> 1.5\text{AU}$, we conclude that the tolerant region of habitable Earths in the Kepler-34 system becomes: $1.6\text{--}2.34\text{AU}$ with $\alpha = 0.3$ and $1.6\text{--}1.98\text{AU}$ with $\alpha = 0.5$ (see Table 2).

3.3. Kepler-35

The equivalent temperature of binaries in Kepler-35 is $T_{\text{eff}} = 5435.5\text{K}$, and the HZ is from 1.2 to 2.0AU with temperature $[210.0\text{K}, 278.9\text{K}]$ (Figures 2(c) and (d)). Both the separation and eccentricity of the binary orbit are smaller than that of Kepler-34, therefore, the HZ boundaries are less influenced ($< 0.01\text{AU}$) by the motion of binaries with time. The same effect occurs in Kepler-38 and 47, in which the HZ boundaries are nearly circular. The initial 100 "Earths" are chosen between $[173\text{K}, 520\text{K}]$ randomly.

Figure 2(c) indicates that 15 "Earths" in the inner region are unstable while other 85 "Earths" outside still orbit the binary stars after 10 Myr, including 36 ($\sim 90\%$) of the initial habitable "Earths" that remained in the HZ. The T_p of the 85 stable "Earths" are shown in Figure 2(d), well fitted by a power law $T_p = 298.8K(r/1AU)^{-1/2}$. We find that the tolerant region of a stable habitable "Earth" with $\alpha = 0$ in the Kepler-35 system is about 1.2-2.0 AU and the variations of T_p of "Earths" in the HZ are all less than 8 K.

Taking $\alpha=0.3$ and 0.5, the location of the HZ will move to an inner region, i.e., 1.0-1.67 AU for $\alpha = 0.3$ and 0.85-1.41 AU for $\alpha = 0.5$. Because smaller HZ overlaps with part of the unstable region, a smaller fraction of surviving "Earths" remain in the HZ in comparison with $\alpha = 0$ (see Table 2).

3.4. Kepler-38

With a radius of $0.3964R_J$, a mass of $\sim 0.078M_J$ for Kepler-38 b is estimated by the density of Neptune in our simulations. The equivalent temperature of binaries is $T_{\text{eff}} = 5496.7K$, and the HZ boundary is [210.5 K, 279.4 K], about 1.6-2.9 AU (Figures 2(e) and (f)). Here The initial 100 "Earths" are chosen randomly from 1.2-4.3 AU with temperature [173K, 350K].

Due to the tight binary orbit, the large distance between "Earths" and the small Kepler-38 b, "Earths" in this system are all stable after 10 Myr (Fig.2e). Finally, 38 ($>90\%$) of the initial habitable "Earths" remaining in the HZ. Fig.2f shows the fitting curve $T_p = 359.7K(r/1AU)^{-1/2}$ and indicates that the boundary of the HZ is from 1.6 to 2.9 AU with $\alpha = 0$. The mean variations of T_p of "Earth" in the HZ are all less than 10K.

The HZ becomes 1.34-2.43 AU for $\alpha = 0.3$ and 1.13-2.05 AU for $\alpha = 0.5$. Since all 100 "Earths" in the Kepler-38 system are stable, most "Earths" in the HZ initially are still habitable due to our simulations while changing the albedo to 0.3 or 0.5 (see Table 2).

3.5. Kepler-47

Using the density of Neptune, we estimate the masses of Kepler-47 b, c as $0.0248M_J$ and $0.0933M_J$, respectively. Their eccentricities are only limited as < 0.035 and < 0.411 , respectively. We choose a mean value for each planet, i.e., $0.035/2 \sim 0.017$ for 47b and $0.411/2 \sim 0.205$ for 47c in our simulations. The equivalent temperature of binaries is $T_{\text{eff}} = 5501.5K$, and the HZ boundary becomes [210.6 K, 279.4 K], about 0.9-1.6 AU (Figure 2(g),(h)). The initial 100 "Earths" are chosen randomly between [173 K, 550 K], about 0.2-2.6 AU.

After 10 Myr evolution, only 66 "Earths" survive and 7 of them are habitable, as shown in Figure 2(g). Since Kepler-47 c is located in the HZ with eccentricity 0.2, it sweeps out a region of 0.8-1.2 AU, as shown in Figure 2(h). Similar to the Kepler-16 system, Kepler-47 c also captures an "Earth" in the 1:1 orbital resonance with a large eccentricity ~ 0.65 ; therefore, this "Earth" has a quite large variation of T_p ($\sim 220K$) and is not habitable. Only "Earths" from 1.2 AU to 1.6 AU survive as habitable "Earths". Due to the perturbation of Kepler-47 c, these habitable "Earths" have a large $dT_p \sim 20K$. Inside the inner boundary of the HZ, there are 14 stable

"Earths", with an even larger $dT_p > 30$ K due to the perturbations of both Kepler-47 b and c.

If the albedo $\alpha = 0.3$, the HZ extends from 0.75 to 1.34 AU, and there will be two tolerant regions for a stable habitable "Earth": 0.75-0.8 AU and 1.2-1.34 AU. With $\alpha = 0.5$, the HZ becomes 0.64-1.13 AU, and the tolerant region becomes 0.64-0.8 AU (see Table 2).

4. TTVS VIA THE ADDITIONAL "EARTH"

Because all the "Earths" have an inclination $= 1^\circ$, we can't observe their transits. To determine the existence of stable "Earths" in the HZ, we can calculate the transit time (T_{tr}) and TTVs of the existing planet in each system, which can be observed by follow-ups. We calculate two T_{tr} with and without an additional "Earth" in each systems, and check their differences dT_{tr} . The initial conditions used here are according to our results in Section 3. The "Earths" labeled as "sample" in Figure 1 and 2, are chosen as the sample cases. The initial conditions of both binary stars and planets in this section are the same with the configurations in the sample cases at the end of simulations (time=10 Myr) in Section 3.

Figure 3 shows the differences of both transit time (dT_{tr}) and TTVs ($dTTV$) in 4000 days in each system. Note that we only show the transits of the larger binary star A in each system. For Kepler-47 system, only the transits of 47 b are considered because the period of 47 c is so long that few transit events can be observed. In Figure 3(a), all systems have increasing variations dT_{tr} . In Kepler-16, the "Earth" is in the corotational resonance with Kepler-16 b, and the interaction between these two planets is strong. Therefore, the dT_{tr} is more obvious than other four systems. The dT_{tr} of Kepler-16 b can achieve $\sim 10^{-2}$ day in 3 years and ~ 1 day in 10 years. The other four systems have small variations due to the limited perturbation of the additional "Earth": $dT_{\text{tr}} < 10^{-3}$ day in 3 years and $dT_{\text{tr}} < 10^{-2}$ day in 10 years. We can sort these five systems by dT_{tr} : Kepler-16 b > Kepler-34 b \sim Kepler-38 b > Kepler-35 b > Kepler-47 b. Figure 3(b) also shows the calculation of the TTV of the existing planets. Similar to dT_{tr} , the strong interaction between Kepler-16 b and co-orbit "Earth" results in a larger $dTTV \sim 0.1$ day. The other four systems have small $dTTV < 10^{-2}$ day.

5. CONCLUSIONS

With the motivation of finding additional "Earths" in the HZs of Kepler-16, 34, 35, 38 and 47, we simulated 100 cases in each system and show the stability and habitability of these "Earths" (see Section 3). After 10 Myr evolution, most "Earths" are unstable in Kepler-16 and we do not find any habitable "Earth". However, two "Earths" in the corotational resonance with Kepler-16 b survived near the outer HZ boundary when the albedo $\alpha = 0$. In Kepler-47, due to the perturbation of Kepler-47 c, only eight "Earths" from 1.2 to 1.6 AU, survive and are habitable. In Kepler-34, 35 and 38, "Earths" in the HZ are stable and most "Earths" in the HZ initially can remain in the HZ. The tolerant region of an additional habitable "Earth" in each system is shown in Table 2.

Different albedos ($\alpha = 0.3$ and 0.5) of the "Earth" make the conclusions a little different. Comparing with $\alpha = 0$, "Earths" absorb less flux and have a lower T_p , i.e., the HZ

migrates to a closer and narrower region. In the Kepler-16 system, we still do not obtain any habitable "Earth" with $\alpha=0.3$ or 0.5 . Kepler-34, 35, and 38 systems have fewer habitable "Earths" that survived and the outer boundaries of the tolerant regions shrink. Overlapping the HZ with the unstable region in Kepler-47, there are two tolerant regions for a habitable "Earth" in Kepler-47 when we set $\alpha = 0.3$, as shown in Table 2.

Comparing the T_{tr} with and without the perturbation of the additional "Earth", we show that: an "Earth" in the same orbit with Kepler-16 b can influence the T_{tr} of

Kepler-16 b obviously, with $dT_{tr} \sim 1$ day and $dTTV \sim 0.1$ day in 10 years. Meanwhile, dT_{tr} and $dTTV$ due to the perturbation of the habitable "Earth" in other systems are relatively small. With the precision of 10^{-3} day ~ 88 s, we can identify $dTTV$ of Kepler-16 b in three years. After 10 years of observations, the $dTTV$ of Kepler-34 b and 38 b can be detected, while the $dTTV$ of Kepler-35 b and 47 b are too small to be detected.

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TABLE 1
STELLAR AND PLANETARY CHARACTERS IN THE FIVE BINARY SYSTEMS.

		Kepler-16	Kepler-34	Kepler-35	Kepler-38	Kepler-47 ^a
Star A	Mass(M_{\odot})	0.6897	1.0479	0.8877	0.949	1.043
	Radius(R_{\odot})	0.6489	1.1618	1.0284	1.757	0.964
	Temperature(K)	4450	5913	5606	5623	5636
Star B	Mass(M_{\odot})	0.20255	1.0208	0.8094	0.249	0.362
	Radius(R_{\odot})	0.22623	1.0927	0.7861	0.2724	0.3506
	Temperature(K)	2800	5867	5202	3315	3357
binary parameters	semi-major axis(AU)	0.22431	0.2288	0.17617	0.1469	0.0836
	period(days)	41.079220	27.7958103	20.733667	18.79537	7.44837695
	eccentricity	0.15944	0.52	0.1421	0.1032	0.0234
	$T_{eff}(K)^b$	4307.8	5892.0	5435.5	5496.7	5501.5
Planet b	Mass(M_J)	0.333	0.22	0.127	0.3964 R_J	0.27 R_J
	semi-major axis(AU)	0.7048	1.0896	0.603	0.4644	0.2956
	period(days)	228.776	288.822	131.455	105.595	49.514
	eccentricity	0.0069	0.182	0.042	0.016	< 0.035
	$T_p(\alpha = 0)^c$	200-215	310-390	370-420	460-490	480-510
Planet c	Mass(M_J)	-	-	-	-	0.42 R_J
	semi-major axis(AU)	-	-	-	-	0.989
	period(days)	-	-	-	-	303.158
	eccentricity	-	-	-	-	< 0.411
	$T_p(\alpha = 0)$	-	-	-	-	267-273

^aData are from Doyle et al., 2011, Welsh et al., 2012, Oroze et al., 2012b, Oroze et al., 2012b and Oroze et al., 2012a respectively.

^b T_{eff} is the effective temperature of the binary system

^c T_p is the equilibrium temperature of planet with albedo $\alpha = 0$.

TABLE 2
MAIN RESULTS IN THE FIVE BINARY SYSTEMS.

	Kepler-16	Kepler-34	Kepler-35	Kepler-38	Kepler-47
Stable "Earth"	7	74	85	100	66
Stable "Earth" in HZ	≤ 2	32	36	38	7
Stable region (AU)	> 0.66	> 1.5	> 1	> 1.1	$0.4-0.8, > 1.2$
Tolerant region (AU)					
$\alpha=0$	~ 0.72	1.6-2.8	1.2-2.0	1.6-2.9	1.2-1.6
$\alpha=0.3$	Null	1.6-2.34	1.0-1.67	1.34-2.43	0.75-0.8, 1.2-1.34
$\alpha=0.5$	Null	1.6-1.98	0.85-1.41	1.13-2.05	0.64-0.8
$dT_p(\text{K})^a$	< 20	< 12	< 8	< 10	< 30
$dT_{\text{tr}}(\text{days})^b$	1	2×10^{-2}	2×10^{-3}	10^{-2}	3×10^{-4}
$dTTV(\text{days})^c$	0.1	10^{-2}	10^{-3}	3×10^{-3}	10^{-4}

^aVariation of T_p with albedo $\alpha = 0$

^bDifference between transit times T_{tr} in 10 years

^cDifferences between TTVs in 10 years

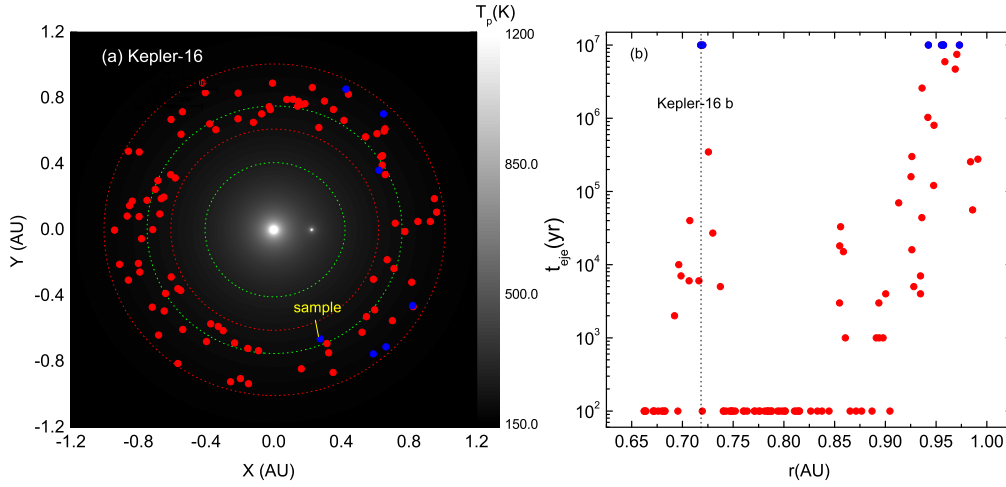


FIG. 1.— "Earths" in Kepler-16: (a) two green dotted lines are the HZ boundaries with albedo $\alpha = 0$. Temperatures of each line are labeled. The two red dotted lines represent the extension of our 100 "Earths", with initial random locations shown in the plot. The red/blue circles represent unstable/stable "Earths" after 10 Myr evolution. The one labeled as "sample" is chosen for the case in Section 4. (b) The ejected time of the 100 "Earths". r is the distance between the "Earths" and Kepler-16 A (and hereafter). The dotted line represents the location of Kepler-16 b.

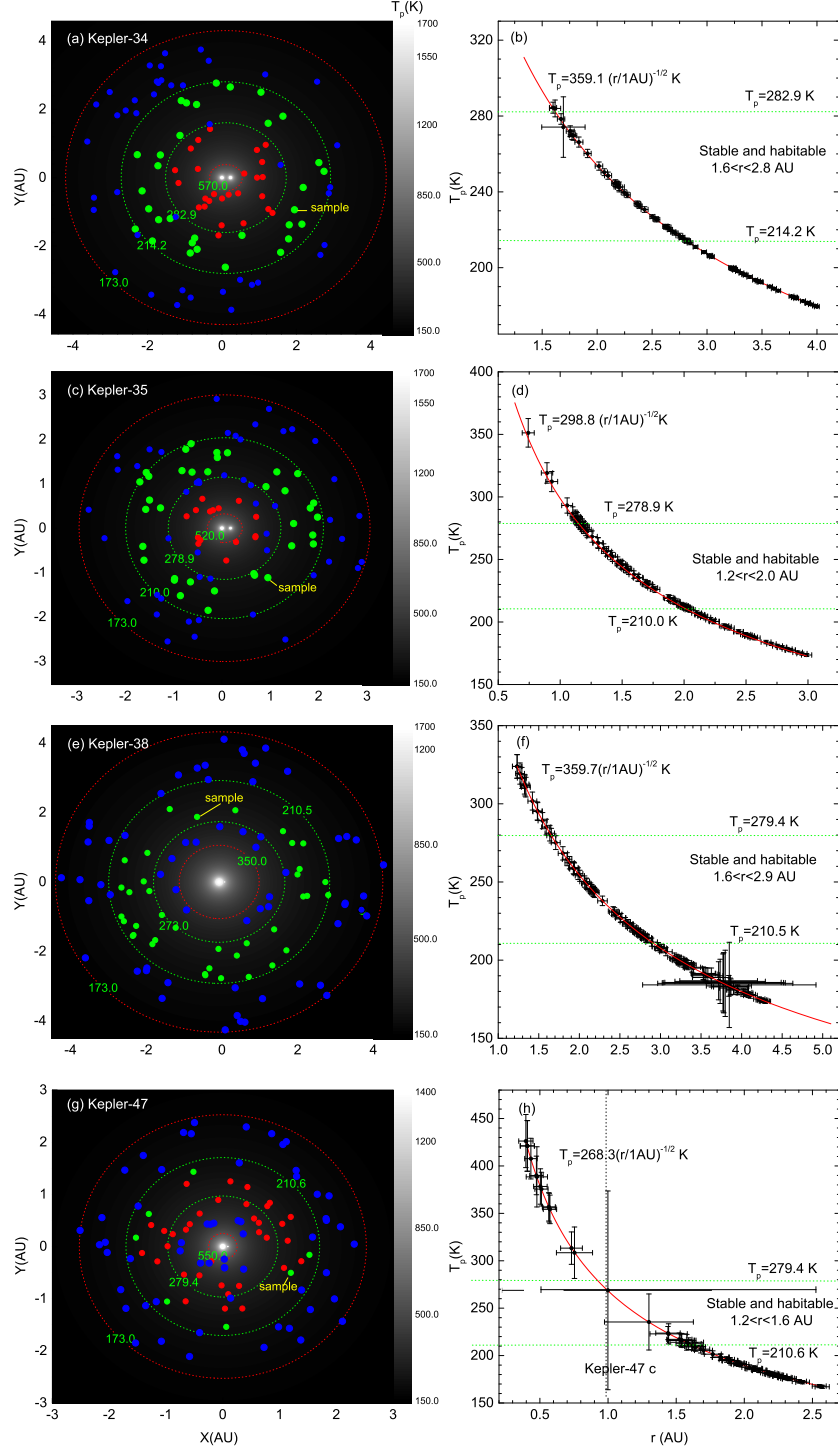


FIG. 2.— "Earths" in Kepler-34, 35, 38 and 47 are represented in panels (a),(c),(e) and (g), respectively: The green filled circles represent stable habitable "Earths", while the red/blue circles stand for unstable/stable "Earths" outside the HZ after 10 Myr. The green and red dotted lines are the boundaries of the HZ and the initial locations of 100 "Earths", respectively. The equilibrium temperature T_p and the location r of stable "Earths" in Kepler-34, 35, 38 and 47 are shown in panels (b),(d),(f) and (h), respectively. The error bars show the largest and smallest values of T_p and r .

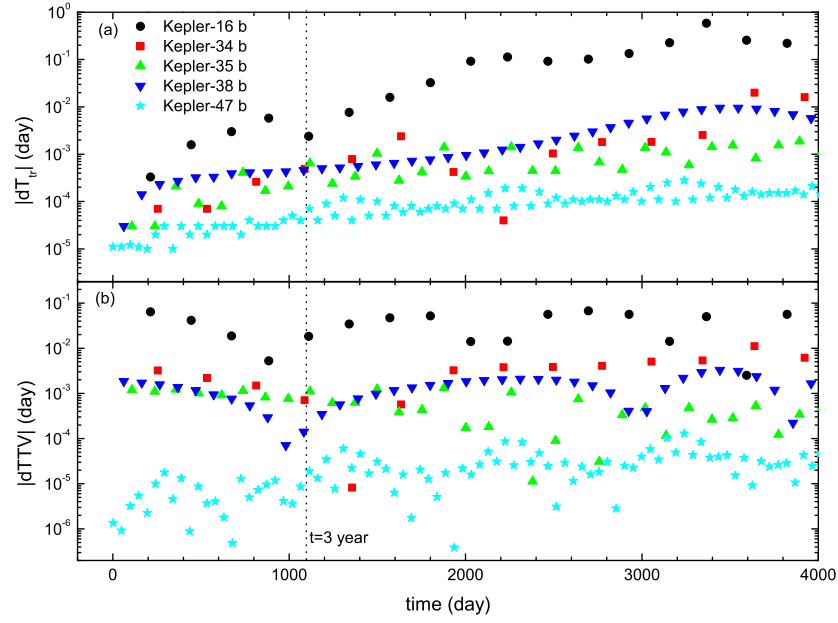


FIG. 3.— Differences of (a) transit times (dT_{tr}) and (b) TTV($dTTV$) of detected planets with and without the perturbation of an additional "Earth". Because of the stronger perturbation between "Earth" and Kepler-16b in 1:1 orbital resonance, T_{tr} and $dTTV$ of Kepler-16b are obviously larger than other four systems, and can be detected in three years.